Investigating the Effects of Encumbrance on One- and Two- Handed Interactions with Mobile Devices

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ABSTRACT
In this paper, we investigate the effects of encumbrance (carrying typical objects such as shopping bags during interaction) and walking on target acquisition on a touchscreen mobile phone. Users often hold objects and use mobile devices at the same time and we examined the impact encumbrance has on one- and two- handed interactions. Three common input postures were evaluated: two-handed index finger, one-handed preferred thumb and two-handed both thumbs, to assess the effects on performance of carrying a bag in each hand while walking. The results showed a significant decrease in targeting performance when users were encumbered. For example, input accuracy dropped to 48.1% for targeting with the index finger when encumbered, while targeting error using the preferred thumb to input was 4.2mm, an increase of 40% compared to unencumbered input. We also introduce a new method to evaluate the user's preferred walking speed when interacting - *PWS&I*, and suggest future studies should use this to get a more accurate measure of the user's input performance.

Author Keywords
Target acquisition; mobile interactions; one- and two-handed input; encumbrance.

ACM Classification Keywords
H.5.2. [User Interfaces]: Input devices and strategies.

INTRODUCTION
One of the benefits of modern touchscreen mobile devices is that they give users a vast array of features and applications that can be used while on the move. Mobile phones can be used in both portrait and landscape orientations and allow users to interact with the device using either one or both hands (text entry, for example). However, in mobile contexts, users are unlikely to be interacting only with their mobile devices as other activities may also be consuming the user's attention, for example moving through the environment and carrying objects such as personal gear and shopping bags. Therefore, a user study was conducted to examine the effects of *encumbrance* and *mobility* on both one- and two-handed interactions with touchscreen mobile phones. Interacting when encumbered has not received much attention from researchers but users often hold and carry cumbersome objects [17,19] or perform manual tasks [21] during interaction and these can cause usability problems. There is currently a lack of interaction techniques to support users when they are encumbered and the results from the experiment presented in this paper will help researchers understand the problems of encumbrance while walking and motivate designers to develop more efficient and effective input techniques to support users when they interact in this way. Our study examines the effects of carrying two shopping bags while using a mobile phone and walking. It is a typical manual task that people perform in their everyday lives and one that can have a significant impact on usability as the user has to struggle between holding both the objects and the device while trying to aim at the touchscreen to input accurately.

To investigate the effects of encumbrance and mobility on both one- and two- handed interactions, three different input postures were evaluated: two-handed index finger, one-handed preferred thumb and two-handed both thumbs while the user was walking and carrying a bag in each hand. The three input postures (see Figure 1) were selected because they are common ways to hold and use touchscreen mobile devices [9,12]. Furthermore, no previous study has compared the impact of encumbrance between the input postures. The one-handed preferred thumb posture is the traditional method of input on mobile phones before the introduction of touchscreen interfaces. Users could press the physical buttons with relative ease because they were within the thumb's reach. However, the introduction of larger touchscreen mobile devices meant that the thumb has more screen space to cover which results in greater thumb movement, especially for those interface components located opposite the preferred hand. This may force the user to change phone grip to reach the onscreen items or switch to a two-handed posture to input more effectively. Two-handed input divides interaction activity between both hands and there are two broad types. In the two-handed index finger posture, one hand holds the device (usually in the non-dominant hand) in a portrait orientation while the other hand is used for input, for example tapping with the index finger or performing ‘pinching’ gestures using both the thumb and the index finger. The other common two-handed grip holds the phone in landscape orientation and input is made by both thumbs. There is no problem reaching items on the screen as, for a typical sized mobile phone, the thumbs can fully cover the screen. Interaction is faster than one thumb or the index finger since two digits are ready for input with the device firmly held in both hands [1]. Furthermore, for some input tasks, interface components can dynamically adjust for better input when the device is held in landscape orientation (wider keys for text entry, for example).

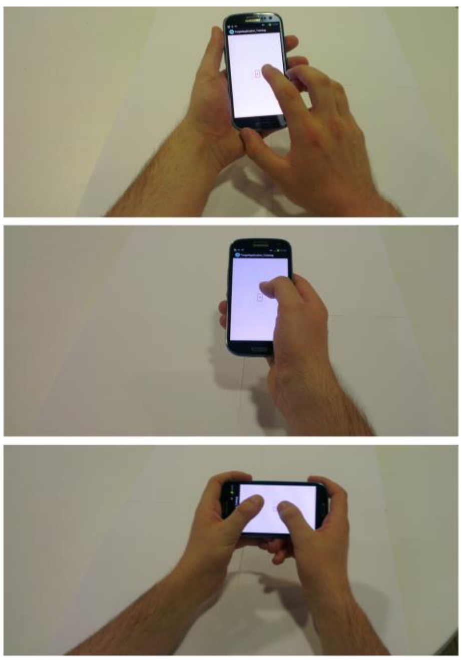

Figure 1. Three common input postures: two-handed index finger (top), one-handed preferred thumb (middle) and two-handed both thumbs (bottom)

BACKGROUND

The Effects of Encumbrance

In one of the earlier studies that investigated encumbrance and its effects on interaction, Ng, Brewster and Crossan [18] extended the work of Crossan *et al.* [6] by examining the practicality of using wrist-based gestures to point on a mobile phone while the user was encumbered. The results showed that holding a bag while performing wrist rotational gestures caused input accuracy to significantly decrease when compared to unencumbered. However, performance while carrying a box under the arm was similar to holding no objects as users were able to steady their forearm against the box which suggested that different types of encumbrances had a varied impact on usability.

Later, Ng, Brewster and Williamson [19] conducted a study which investigated the impact of encumbrance on mobile interactions. Prior to their main experiment, an observational study was carried out in three public settings to identify the common objects that users held and carried during interaction with mobile devices. During six hours of observation, they saw people carrying 878 objects, 554 of these were being held when users were interacting. Approximately 46% of the objects they observed were bags and 36% were boxes (the remaining objects included umbrellas, cardboard cups and pushchairs). Their data showed that using mobile devices while carrying objects is a frequent occurrence and therefore is an important use-case that should be studied to help users interact effectively. The results from their target acquisition experiment showed users were significantly less accurate at targeting on a touchscreen phone when either carrying a bag in the hand or holding a box under the arm while walking compared to unencumbered and standing still. Furthermore, there were significantly more hand movements and instability when the dominant hand or arm was encumbered compared to the non-dominant side. Users only selected targets using the two-handed index finger input posture in this study.

In a follow-up study, Ng and Brewster [20] investigated the trade-off between encumbrance and preferred walking speed (PWS) when targeting using the two-handed index finger posture. Input accuracy is often improved when the user’s walking speed slows down [3]. Similar to [19], the results showed that carrying a bag or a box while maintaining the preferred walking speed (PWS) caused significantly more error than unencumbered and in a stationary position. Targeting error increased by as much as 112% while walking at the PWS and carrying a bag. This shows some of the problems that can occur when trying to use a mobile device when walking and encumbered. In this case, however, users were only carrying one bag or box so interaction is likely to be even worse when more items are carried while on the move.

Oulasvirta and Bergstrom-Lehtovirta [21] looked at physical multitasking during interaction by examining how performing common daily activities that require the user’s hands influenced input performance on both desktop and mobile devices. Twelve physical tasks covering a range of different hand grips were assessed including holding differently sized objects ranging from a ballpoint pen (small), cigarette packet (medium) to a basketball (large) while either performing a pointing task on a laptop or text entry on a mobile device. Other objects were also assessed such as using a pair of scissors that required a more intricate and complex finger grip. The results from the text entry experiment showed one-handed typing on the mobile phone while holding an object (such as a mug) caused the user to input less accurately when compared to two-handed typing. This study did not look at mobility which could have compounded some of the problems they found. Ng *et al.* [19] observed users holding similar smaller-sized objects such as cups when using mobile devices in public settings.

Mainwaring, Anderson and Chang [17] conducted an ethnographic study across three major cities to examine the types of objects that young professionals carried in their everyday activities and how those items were used in the urban environment. The so called 'mobile kits' – the objects that the observed participants carried daily – included mobile technologies (phones, cameras and iPods), books, wallets and keys. Similar to [19], they found the participants across all three cities frequently carried different types of bags to transport their belongings. Jain [10] observed female users and found they typically carried their mobile phones in a handbag along with other personal belongings to prevent pick-pockets or items tumbling out. One of the subjects, who was constantly on her mobile phone for work (to purchase goods, arrange meetings with colleagues) while having to carry heavy and bulky boxes had interaction issues as she struggled to multitask. Perry *et al.* [24] investigated the role of technology and artefacts to support mobile workers (those who are not limited to an office space) and found users to carry objects ranging from PDAs and laptops to paper-based objects such as notebooks, working files and folders. These studies highlight the wide range of objects and situations that can encumber users and the need to understand how performance is affected so that we can design better interaction techniques to support them. Sherry and Salvador [26] commented that ordinary users may not have the skills or experience to perform multiple activities in a uniform and synchronised manner and suggested that, as interface designers, we need to understand the situations that users experience on a daily basis and develop more efficient and stress-free ways of interacting with computing devices.

One- and Two- Handed Interactions

Observational studies have been conducted to examine the common ways that users interact with mobile devices. Karlson, Bederson and Contreras-Vidal [12] studied one-handed interaction by conducting a field study in an airport to examine user behaviour with mobile devices. Their observations suggested that 60% of users engaged with their mobile phone in a one-handed posture when walking. A follow-up survey suggested 45% of participants would use one hand only for all device interactions compared to 19% for two-handed interactions. Users were also seen to carry objects during input but encumbrance was not examined specifically in their study. More recently, an investigation by Hoober [9] who made over 1000 observations of users in different public settings including bus stops and cafes found that 49% of people used their mobile phone in the one-handed preferred thumb posture, while 36% held the device in the two-handed index finger position to input. The remaining 15% of users held the device in the two-handed both thumbs posture. This shows the need to evaluate the effects of encumbrance on thumb-based input on mobile devices that previous studies [18,19] did not examine.

Studies have also been conducted to investigate and improve both one- and two- handed interactions. Parhi, Karlson and Bederson [22] examined target size for single thumb-based interaction and recommended target size of at least 9.2mm for discrete selections and slightly bigger target size of 9.6mm for continuous targeting. This study, however, did not evaluate one-handed thumb input while encumbered or walking. Later, Perry and Hourcade [23] extended the work of Parhi *et al.* [22] by examining one-handed thumb targeting and walking but unencumbered. The results from their study showed that users were more accurate and quicker at tapping with the preferred hand. Also, users preferred to select targets that were located in the centre of the device as they were subjectively easier but accuracy was actually higher for targets at the edge of the screen, especially for those targets near the input hand. Surprisingly, there were no significant differences in performance between standing and walking (participants walked at their normal pace in a hallway). Karlson and Bederson [13] tried to address the issues caused by one-handed thumb interaction and developed ThumbSpace which allowed users to configure the preferred screen area to select difficult to reach onscreen objects. Participants preferred to use the application for targets that were biomechanically difficult for the thumb to reach. Boring *et al.* [4] used the thumb's contact area to allow users to input efficiently on a touchscreen in the one-handed preferred thumb input posture. The results indicated that the technique worked well for small targets.

Kim *et al.* [14] used capacitive touch sensors on a prototype device to detect different hand grip positions which included the one- and two- thumb input postures. Later, Goel *et al.* [8] managed to use the built-in inertial sensors from a mobile phone to infer the user's hand posture while in a stationary position. The results showed that their application could accurately distinguish between the one-handed thumb and two-handed index finger input postures. The two-handed both thumbs position was not assessed. Azenkot and Zhai [1] compared text entry performance using the index finger, one thumb and both thumbs on a touchscreen device. Their results showed that typing with both thumbs was significantly faster than one thumb or the index finger. However, error rate was significantly higher for text entry using both thumbs which indicated a speed-accuracy tradeoff. Later, Goel *et al.* [7] examined the user's touch pattern to distinguish between the three input postures to improve text entry. Yin *et al.* [27] also used hand posture to enhance text entry on touchscreen keyboards and reported that their method could differentiate single finger and two thumbs typing with an accuracy of 86.4%.

The studies discussed here have all compared input performance of the common hand postures that users adopt when interacting with mobile phones. Some researchers have also examined the effects of mobility. However, no previous studies have looked at the impact of encumbrance and mobility on all of the three common input postures. The studies that have examined encumbrance ([19,20]) only evaluated targeting using the index finger. Therefore, we conducted an experiment to compare the effects of encumbrance while walking using three typical input postures to see how targeting performance on a touchscreen interface is affected.

EXPERIMENT

A within subjects experiment was designed to test the impact of carrying a bag in each hand while walking at a constant speed around a pre-defined route and performing target selections with a touchscreen mobile phone held in three common input postures.

Encumbrance Scenario

A typical supermarket carrier bag was chosen to evaluate the impact of encumbrance because it is a common object that people carry often in their daily lives [17,19]. The participants in our experiment held one bag in each hand to simulate situations where the user is carrying multiple objects. The bags were identical and the dimensions (cm) were approximately 33 x 48 x 6 (w x h x d). Each bag weighed 1.6 kilograms to replicate the effects of holding a realistic object yet keep the amount of fatigue and strain on the participants to a minimum. Figure 2 shows a participant carrying the bags during interaction.

Figure 2. A participant carrying the bags during one- (right) and two- (left) handed input.

Measuring and Maintaining the PWS

A pre-defined oval route (Figure 3) was created to examine encumbrance and mobility. The route was marked out using plastic cones in a spacious and open room and measured 20m in total length and was 1.2m wide. Participants were instructed to keep within the path during the experiment.

Three versions of each participant's preferred walking speed (PWS) were recorded before the experiment began:

PWS – Each participant was instructed to walk around the route for five laps at a pace that he/she would normally walk. The total amount of time required was recorded and the average walking speed was calculated, denoted as *PWS*. This is the standard measure of PWS [25]. No mobile device was used nor bags carried.

PWS&E – The first step was repeated but participants carried one bag in each hand to measure any change in PWS due to encumbrance. The calculated walking speed is denoted as *PWS&E* and gave us a baseline for walking speed when encumbered.

PWS&I – The first step was repeated again but participants also performed a targeting task on a smartphone to measure walking speed during interaction (but unencumbered), denoted as *PWS&I*. This gave us a baseline for walking performance when interacting. All participants performed the task in the two-handed index finger posture for consistency (this is the most commonly used input posture in mobility studies [3,19,20]). Although the same targeting task was used in the main experiment, targets for each condition were randomly ordered to keep bias and learning effects to a minimum.

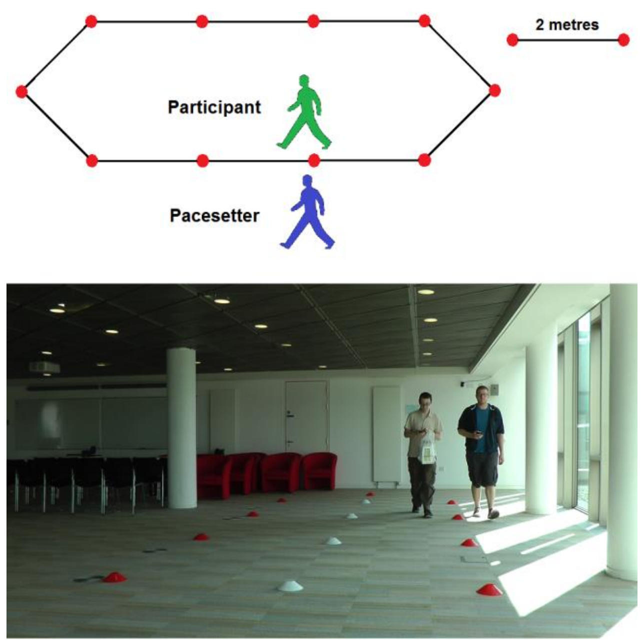

Figure 3. The pre-defined oval route marked out by plastic cones (red dots) is shown in the top image. The distance between each cone is 2m. During the experiment, the participant (green figure) maintained their PWS by walking side-by-side with the pacesetter (blue figure). Part of the actual route is displayed in the bottom image.

Once the walking speeds had been calculated, the experiment began and each participant walked at their individual PWS&I for each input posture condition. Participants walked side-by-side with a pacesetter who walked at the calculated PWS&I by using a metronome application that ran on a HTC One X phone. At the end of the experiment, the PWS and PWS&E were both measured again to assess any fatigue caused by interaction and carrying the bags.

We chose the approach of controlling walking speed, which is unusual for mobile evaluations, as it meant we could remove one variable from our results. In studies where walking speed is not controlled (e.g. [2,15,16,19]), participants can trade-off input performance and walking speed. It can be then difficult to understand these choices and therefore make recommendations based on the results. If we control walking speed then we can isolate the effects of targeting accuracy, error and selection time. The question then arises as to what walking speed should be used. In this paper, we chose a new measure: PWS&I, or the walking speed that a user naturally walks when using a device. Other studies have used different approaches; Kane *et al.* [11] do not explicitly state the walking speed they used but they trained a pacesetter to walk at a constant speed across all participants, rather than being based on a user's own normal walking speed. Ng *et al.* [20] used each participant's PWS, but this is not the speed at which a user would walk when using a device. So, in our study, we used PWS&I so that we could see the effects of encumbrance when interacting on the three input postures.

Experimental Task

The task was to select a series of targets one at a time on a touchscreen mobile phone as quickly and as accurately as possible. There were nine target positions evenly spaced in a 3 x 3 grid, as shown in Figure 4.

Figure 4. The targeting task ran on a Samsung S3 phone. The positions of the targets are shown in both orientation modes.

The centre and outer targets were selected in an alternate sequence - every second selection was an outer target – and the order of the outer targets were randomized for each block. Each outer target was selected ten times which resulted in 160 target selections per block and there were two blocks for each condition. Like Crossan *et al.* [5], there was a random interval ranging from 0.5 and 1.5 seconds between a selection and the next target being shown to negate any rhythm created between the participant's walking and onscreen targeting. A Samsung Galaxy S3 smartphone with a touchscreen resolution of 720 x 1280 pixels (~12 pixels/mm) was used. Each target was 60 pixels (5mm) wide and 96 pixels (8mm) long with the central crosshair measuring 30 pixels (2.5mm) in both directions. This is the size of a key on the standard keyboard for this phone. The device was held in portrait orientation for both the two-handed index finger and one-handed preferred thumb input postures. The device was used in landscape mode for the two-handed both thumbs posture with the bottom end of the device always to the right for consistency (see Figure 4). Participants were given a short training phase at the start of the experiment to familiarise with the targeting task in each input posture.

Participants

Eighteen participants (11 males) recruited from the university took part in the experiment. The mean age was 25 years (SD = 3.519) and all participants preferred using their right hand for interaction (despite one individual being left-handed). Sixteen participants owned and used a touchscreen mobile phone daily while two users occasionally used touchscreen phones. Participants were paid £6 for their participation.

Experimental Design

The participants performed the targeting task either unencumbered or carrying a bag in each hand for each of the three input postures which resulted in a total of six conditions. Each condition was conducted while walking at the PWS&I by following a pacesetter around the route. A within-subjects design was used and the conditions were counterbalanced. The Independent Variables were type of encumbrance (2 levels - unencumbered and carrying the bags) and input posture (3 levels - two-handed index finger, one-handed preferred thumb and two-handed both thumbs). The Dependent Variables were target accuracy, target error and selection time. Target accuracy was measured as the percentage of successful target selections; the position pressed on the touchscreen was either within the target border or not. Target error (in millimetres) was the absolute distance from the centre of the target to the recorded touch down position. Selection time (in milliseconds) was the duration from the display of the current target to the instance that a press down event was logged.

The main hypotheses of the experiment were:

H1: Participants will be significantly less accurate at target selection when encumbered compared to unencumbered, while walking at their PWS&I;

H2: Participants will be significantly less precise at target selection when encumbered compared to unencumbered, while walking at their PWS&I;

H3: Participants will take significantly more time to target when encumbered compared to unencumbered, while walking at their PWS&I;

H4: Target selection using both thumbs will be significantly more accurate, precise and quicker than input using one thumb or the index finger when encumbered;

H5: The PWS will be slower when encumbered or interacting with a mobile device than walking alone.

RESULTS

Each participant completed 12 blocks of targets – six condition and two blocks per condition. There were 160 targets for each block giving a total of 1920 targets per participants and 18 participants resulted in a total of 34,560 targets for the whole experiment. To filter out unintentional selections, targets that took less than 100 milliseconds to select were removed from the data. As a result, 23 targets were eliminated from the final data set. Two-factor repeated-measures ANOVAs with type of encumbrance (2 levels) and type of input posture (3 levels) as factors were conducted to analyse accuracy, error and selection time.

Target Accuracy

The ANOVA for target accuracy showed a significant main effect for encumbrance, $F(1,17) = 87.880$, $p < 0.001$. *Post hoc* pairwise comparison with Bonferroni corrections showed that the participants were significantly more accurate when unencumbered compared to carrying the bags (mean difference = 11.702, $p < 0.001$). There was no significant main difference between the three input postures $F(2,34) = 2.113$, $p > 0.05$. A significant interaction was observed between the factors, $F(2,34) = 3.757$, $p < 0.05$. Encumbrance caused accuracy to significantly decrease for each input posture when walking. Based on these results, hypothesis H1 is supported. Figure 5 illustrates the mean target accuracy for each condition. The graph shows the participants were more accurate at targeting when unencumbered than carrying a bag in each hand for each input posture.

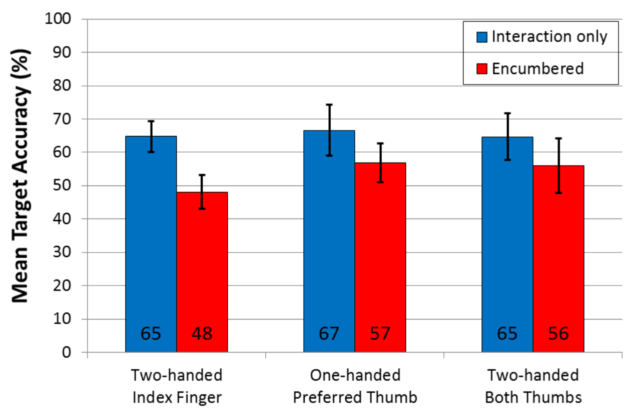

Figure 5. The mean target accuracy (%) for each condition. The blue and red bars illustrate the unencumbered and encumbered conditions respectively. Error bars denote 95% CI.

Target Error

The ANOVA for targeting error showed there was a significant main effect for encumbrance, $F(1,17) = 32.753$, $p < 0.001$, where error was significantly higher when the user was encumbered than unencumbered (mean difference = 0.941). There was no significant main effect for input posture, $F(2,34) = 0.481$, $p > 0.05$. The interaction between the two factors was not significant, $F(2,34) = 0.857$, $p > 0.05$. Based on these results, hypothesis H2 is supported. Figure 6 shows the mean targeting error for each condition. Error was evenly matched when users were unencumbered. As target selections got more physically challenging (by carrying the bags at the same time), error increased for each input posture.

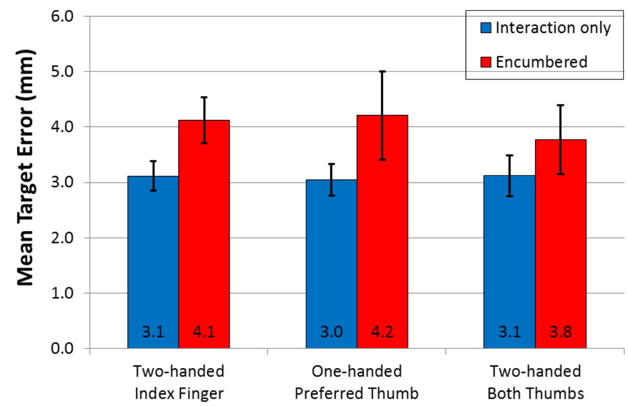

Figure 6. The mean target error (millimeters) for each condition. Error bars represent 95% CI.

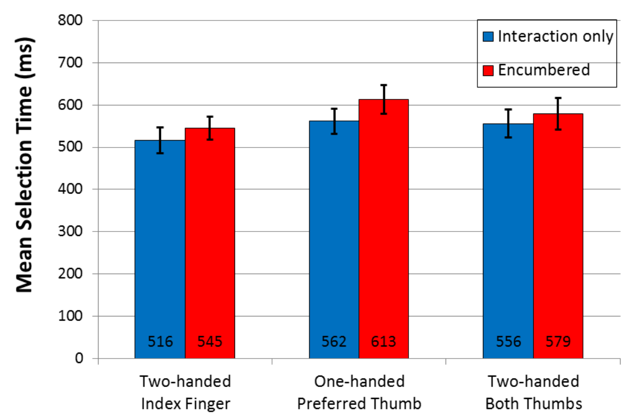

Figure 7. The mean selection times (milliseconds) for each condition. Error bars represent 95% CI.

Selection Time

The ANOVA for selection time showed a significant main effect for encumbrance, $F(1,17) = 11.672$, $p < 0.05$, where target selections took significantly longer when carrying the bags than interaction only (mean difference was 34.6 ms). There was a significant main effect for input posture, $F(2,34) = 13.646$, $p < 0.05$. *Post hoc* pairwise comparisons with Bonferroni corrections showed a significant difference between all pair combinations, except between the two thumb-based input postures. Target selection using the one-handed index finger posture was significantly quicker than the one-handed preferred thumb and two-handed both thumbs poses. Input using both thumbs was not significantly quicker than the preferred thumb. A significant effect was also observed for the interaction between the two factors, $F(2,34) = 3.924$, $p < 0.05$. Encumbrance caused significantly slower selection time for each input posture than unencumbered. The biggest negative effect was on the one-handed preferred thumb posture when encumbered. Figure 7 shows the mean selection times for each condition. Target selection took the longest in the one-handed preferred thumb posture when encumbered. Based on these results, hypothesis H3 is supported. However, hypothesis H4 is rejected since there was no significant difference between the input postures for accuracy and error. Furthermore, input was quicker when the index finger was used to target.

Performance of Individual Target Positions

The performance of each individual target position for the three input postures is shown in Figure 8, Figure 9 and Figure 10. The results for the two-handed index finger input posture showed that error was evenly matched for each target position when unencumbered and encumbered. The variability in taps for each target location is greater when encumbered (as shown by the larger red ellipses), especially the targets on the left of the first and second rows. Encumbrance caused accuracy to decrease for all target positions, with accuracy dropping to 41% for the target in the top left corner.

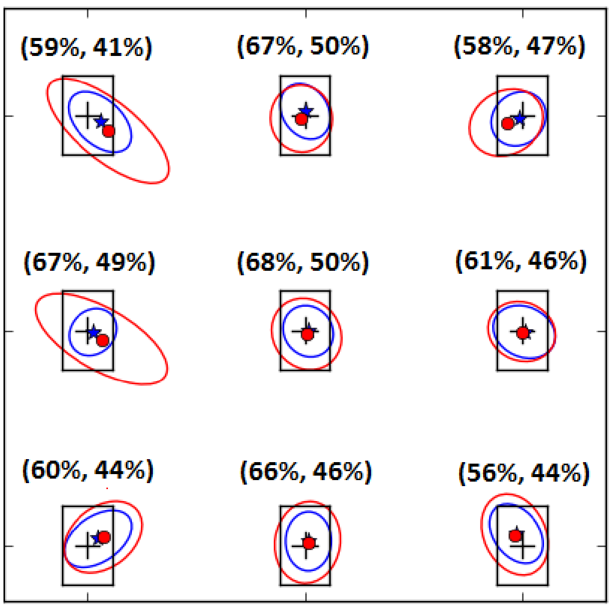

Figure 8. The mean and covariance of the x and y targeting error for each target position when unencumbered (blue) and encumbered (red), for the two-handed index finger input posture. The figures above each target show the accuracy (%) when unencumbered (left) and encumbered (right).

The results for the one-handed preferred thumb input posture show greater variability in tapping performance between unencumbered and carrying the bags. The four targets (middle and right targets on the second and third rows) had similar error when unencumbered and encumbered. All participants used their right thumb to input therefore these targets were the closest. There was a greater difference in error between tapping when unencumbered and encumbered for the other five target positions as these targets required more thumb movement to reach. The left target on the first row was affected the most when encumbered as it had the highest mean error and lowest target accuracy of 31%. The ellipse for the target in the top-left corner when encumbered also highlights a much greater spread of taps than the other target positions which suggest participants had the most difficulty to select the target that was the furthest away from the thumb.

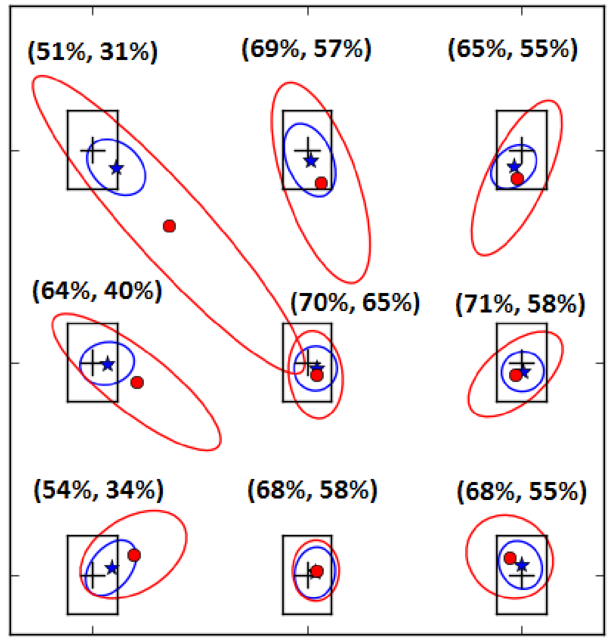

Figure 9. The mean and covariance of the x and y targeting error for each target position, for the one-handed preferred thumb input posture.

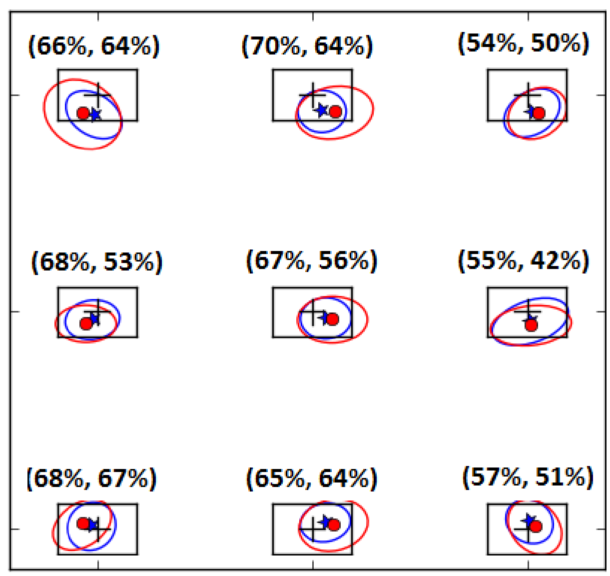

Figure 10. The mean and covariance of the x and y targeting error for each target position. for the two-handed both thumbs input posture.

The tapping performance for the two-handed both thumbs input posture showed that error was evenly matched for all target positions between unencumbered and encumbered.

The mean errors for the three targets in the middle column illustrate an offset to the right which may suggest that the participants mainly used their right thumb to tap those targets. Target accuracy for the three targets in the right column was lower than the three targets in the left column for both unencumbered and encumbered, despite all participants preferred using their right dominant hand to input.

Comparison of Walking Speeds

We wanted to compare the different classes of walking speed discussed earlier to see how they differed as no previous study has measured the walking speed when encumbered but not interacting. The mean walking speeds for PWS, PWS&E and PWS&I recorded at the start of the experiment are shown in Table 1. A one-factor ANOVA with walking speed as factor (3 levels) showed a main effect, $F(2,34) = 52.281$, $p < 0.01$. *Post hoc* pairwise comparisons with Bonferroni corrections showed that the participants walked significantly slower when interacting (PWS&I) than walking and encumbered, and walking alone. There was no clear difference between PWS and PWS&E (given the objects we chose for our study). Therefore, hypothesis H5 is partially supported.

Walking Speed	Mean (km/h)	SD (km/h)
PWS	4.9	0.5
PWS&E	4.9	0.6
PWS&I	4.1	0.4

Table 1. The mean PWS (top row), when encumbered (middle row) and during interaction only (bottom row).

DISCUSSION

The results from the experiment showed that targeting performance on a touchscreen interface was significantly affected when users were encumbered by carrying a bag in each hand and walking at their PWS&I across three common input postures. Target accuracy was evenly matched between the three input postures when users were unencumbered. However, once the users were encumbered, accuracy decreased; the two-handed index finger input posture dropped by 16.7% compared to 9.9% and 8.7% for the one- and two- handed thumb input methods respectively. We anticipated that using both thumbs would be more accurate than the preferred thumb and the index finger. However, there were no big differences between the input postures which suggest the method of input does not greatly affect interaction for target accuracy when encumbered.

The results for targeting error showed that users were significantly less precise when encumbered compared to unencumbered. Like target accuracy, the mean error was similar for each input posture when unencumbered. However, the one-handed preferred thumb input posture was affected the most when carrying the bags, as error increased by 40%. For two-handed input, error increased by 32.3% and 22.6% for the index finger and both thumbs input postures respectively. There were no significant differences between the three input postures, as targeting error was similar when unencumbered or carrying the bags. If input precision is important, then no one posture can be clearly recommended for input when encumbered and walking. Furthermore, two-handed tapping might not result in more precise targeting than one-handed input. This shows that we need to take encumbrance into account when designing new interaction techniques for mobile devices.

The results for selection times showed users were significantly slower at targeting when encumbered compared to holding no objects. However, the differences were marginal - the biggest reduction of 51ms was caused in the one-handed preferred thumb posture. This posture also resulted in the slowest mean selection time when the user was encumbered. The user is effectively performing three manual tasks in one hand only: holding the device, attempting to target and carrying the bag, which makes interaction slower and more difficult. In the two-handed postures, the activity is divided between both hands with less cost to performance. The two-handed both thumb input posture was significantly faster than using the preferred thumb but significantly slower than the two-handed index finger posture. We anticipated that users would be faster at targeting when using both thumbs due to the advantage of having an extra digit to input. This suggests when the user is encumbered and walking, there is a speed-accuracy trade-off when using both thumbs to target. Azenkot and Zhai [1] reported a similar finding when they compared these three input postures for static text entry on a mobile device.

We also examined each individual target position for a more in-depth analysis of user's performance for each input posture. There was a greater distribution of taps for each target position when encumbered compared to unencumbered for the two-handed index finger input posture. The mean error between unencumbered and holding the bags was similar for each target position despite a greater difference in target accuracy. Users were least accurate at selecting the left target in the first row when encumbered and using the index finger to target. Since all participants preferred using their right hand to interact, there was likely to be a bias effect on the user's starting position to input. Targets on the left side of the device would therefore require more finger movement to select. Those targets might have been more difficult to reach when encumbered.

Like the two-handed index finger input posture, there was greater variability of taps for each target position when encumbered compared to unencumbered, for the one-handed preferred thumb posture. The targets that were closest to the thumb used for input were selected more accurately and precisely when encumbered than those that were further away and biomechanically difficult to reach. This was illustrated by the poor performance of the left targets in the first and third rows where accuracy dropped to 31% and 34% respectively. Users who have smaller thumb lengths would have had more difficulty to reach the targets located the furthest distance away from the thumb. Also, participants might have had difficulty adjusting their hand grip to reposition the device in an attempt to select those targets that are biomechanically challenging to tap when using the preferred thumb to input and holding the bag as well.

The distribution of taps for each target position was similar between unencumbered and holding the bags for the two-handed both thumbs posture. Target accuracy was evenly matched for the targets on the first and third rows. There was a greater difference in accuracy between unencumbered and encumbered for the targets on the second row. Interestingly, the targets on the right column were less accurate than the targets on the left column, which suggests holding a bag in each hand affects the user's dominant hand more than the non-dominant hand. Ng *et al.* [19] showed similar findings and reported that when the user's dominant hand or arm was encumbered, performance dropped significantly more than holding objects in the non-dominant side. However, users in their study only used the index finger to input.

The walking speeds calculated in our experiment allowed us to examine the effects of encumbrance and interaction on the user's PWS. The participants managed to carry the bags (weighing 1.6 kg each) without a major impact on walking speed – PWS and PWS&E were similar. However, as anticipated and shown in previous studies [2,3], the PWS&I dropped by 16.3% when compared to PWS. For comparison, Ng *et al.* [19] reported a similar decrease in walking speed of 16.7% when users were targeting on a touchscreen mobile phone, while Bergstrom-Lehtovirta *et al.*[3] found users to drop their PWS by 24% during interaction when on a treadmill. The targeting error when walking at PWS&I for the two-handed index finger input posture was 4.1mm. Ng *et al.* [20] used the same targeting task as ours and reported an error of 5.8mm when using the index finger to target but walking at the PWS. The mean walking speed from their study was 4.8km/h which suggests walking faster may overestimate the decline in performance. We recommend using PWS&I in future mobile studies for a more accurate representation of the user's input performance when walking.

We were also interested to see if users could maintain their walking speed at the end of the experiment because the results would give some indication of the fatigue caused by prolonged periods of interaction while encumbered and walking. The participants took an average of 18.3mins (SD = 1.9) to complete all six conditions. Once all of the targeting tasks were complete, the PWS and PWS&E were both measured again for each participant, both giving a mean walking speed of 4.9 km/h once again. This showed that participants were not significantly fatigued during the study and that they could walk with the bags without any problems. The mean distance walked to complete all 12 blocks was 1480.2m (~67 laps of our route). This suggests that fatigue may not have been a confounding factor that could have affected the user's targeting performance, although, the user's physical condition should always be taken into consideration. Participants in our experiment were only carrying 3.2kg during the study and it is likely that heavier items would cause more fatigue, a bigger impact on PWS and potentially more encumbrance problems.

Researchers and designers should consider the targeting errors from our experiment when defining the size of keys, buttons and other interface components. We recommend a radius of at least 4.2mm for small components to allow users to input more accurately when encumbered and walking. Input posture should also be considered when developing new techniques to help users input more accurately when carrying cumbersome objects while on the move. The results from our experiment showed that when unencumbered, there were no big differences between the postures in any of our metrics. The two-handed both thumbs input posture was generally the most suitable method to use when both hands were encumbered. So, a recommendation from our study is when using a mobile phone encumbered switch to the two thumbs posture! Also, if mobile devices could accurately detect the input posture then applications could automatically correct some of the input errors that are likely to occur to assist the user to interact with the touchscreen in a more efficient manner. For example, dealing with the large target distributions that occur around the left and top edges of the screen when using the one-handed preferred thumb input posture. Goel *et al.* [8] showed promising results when using built-in sensors in a mobile phone to predict the user's hand posture in a static position. Future studies should investigate if a similar technique can be used to correctly detect the different input postures while the user is encumbered and walking.

CONCLUSIONS

The study presented in this paper shows that researchers should consider the effects of encumbrance and mobility when designing new input techniques and applications. Encumbrance is often overlooked yet people frequently hold and carry objects such as shopping bags, boxes and umbrellas, which can make interaction less accurate, slower and more difficult while on the move. The results from our experiment have shown that input accuracy decreased while both targeting error and selection time increased significantly when carrying a bag in each hand during interaction. In general, encumbrance caused targeting performance to significantly decline for both one- and two- handed input. We compared three common input postures and showed the difference in targeting performance for each posture when the user was encumbered and walking. No previous studies have made this comparison. We introduced a new method to evaluate the user's walking speed; the preferred walking speed when interacting - *PWS&I*. This is the walking speed at which users walk on the ground when using mobile devices. Future studies should use this method when assessing interaction while walking to get a better reflection of the user's input performance.

Encumbrance as a research topic is still at its early stages yet usability issues are evident, therefore it deserves more focus from researchers in the HCI community. Users are frequently challenged with physical encumbrances that can make using mobile devices awkward and error prone. If more effective and efficient interaction techniques are developed, then the large number of applications and services available on smartphones will be more usable in a much wider range of contexts, which will be beneficial for users.

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